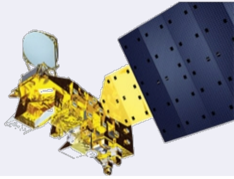
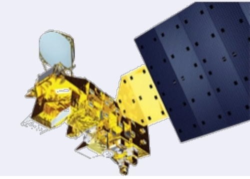


AIRS V6 CO2 Product Development

Edward Olsen, Stephen Licata
Jet Propulsion Laboratory, California Institute of Technology

AIRS Science Team Meeting
21-23 April 2015

V6 CO2 Product Development - Outline



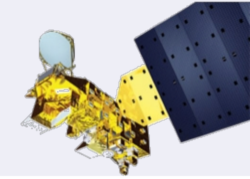
- Transition to SARTA V6
  - Execution time challenge
  - Why transition to SARTA V6 is necessary
    - Steps taken
  - Successful transition, and the expanded QC now possible
    - Requiring stability with respect to perturbation of first guess
      - Elimination of runaway solutions
      - Identification of solutions not well-constrained by radiances
    - Identifying unrealistic solutions using calculated AKs

- Interim Validation via *in situ* airborne measurements extended with CarbonTracker
  - INTEX-NA, INTEX-B and HIPPO-1 through HIPPO-5

- Next Steps
  - Quantify impact of removal of fine structure in temperature profile and of perturbation of stratospheric temperature
  - Validate via *in situ* airborne campaigns with added Tair collocation constraint
  - Direct comparison of retrievals over globe to CarbonTracker
  - QC optimization
  - Operationalize code and document
  - Probe deeper in troposphere

Transition to SARTA Version 6 – The Necessity

(StandAlone Rapid Transmittance Algorithm)



- V5 Operational VPD CO2 retrieval uses SARTA RTA107
  - RTA107 –fixed “at launch” coefficients common to all channels
    - Allows execution for subset of channels (typically use ~100 for VPD)
    - **Execution time ~5 min/granule (1350 FOVs/granule)**
      - 24 concurrent runs on “dry” multi-CPU node requires 1.5 days per month of data
  - RTA108 – updated fixed coefficients derived after 28 Oct 2003 CME forced Aqua shutdown and the subsequent AIRS recovery cool down
- V6 Operational VPD CO2 retrieval will use SARTA Version 6
  - V6 –interpolated coefficients incorporating scan-dependent Doppler shifts and orbit-dependent module shifts for every channel
    - Original code required execution for full channel set (2378)
    - **Execution time ~2.5 hr/granule (1350 FOVs/granule)**
      - 24 concurrent runs on “dry” multi-CPU node requires 1.5 days per day of data
- Why is transition to SARTA V6 necessary?
  - A decade of mission data were analyzed to determine orbital and Doppler impacts on spectra
    - YOFFSET, the frequency shift of channels, is the sum of focal plane drift, the shift of each AIRS channel with respect to the mid-point of its detector module and the Doppler shift of the scene
      - V6 RTA has a three sets of pre-calculated coefficient sets for calculation of instantaneous channel frequency
      - Depending upon orbit, scan angle and channel, the coefficients are interpolated to calculate the instantaneous frequency of an AIRS channel
    - Additional CO2 (secant angle) and non-LTE (CO2 amount) predictors added
    - Correction of solar secant angle calculation beyond 80 deg
    - Transmittance tuning changes (affecting CH4 and N2O channels)
  - Comparison of CO2 retrievals using SARTA RTA 108 and V6 while ingesting identical Level 2 input indicate that **impact of YOFFSET is non-negligible**

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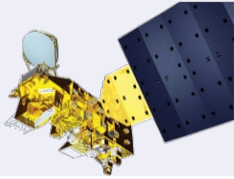
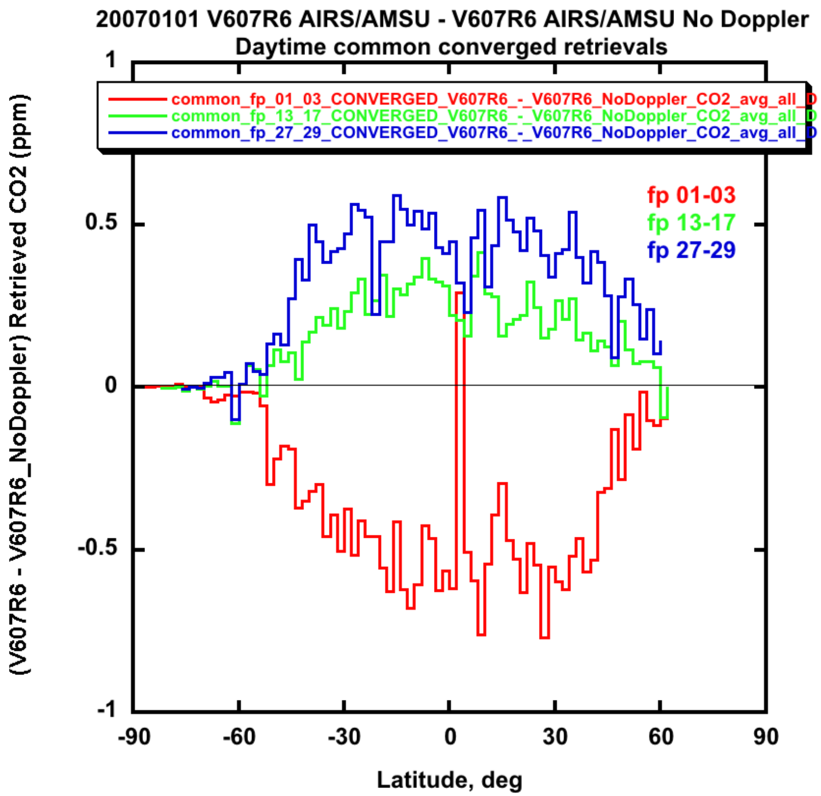
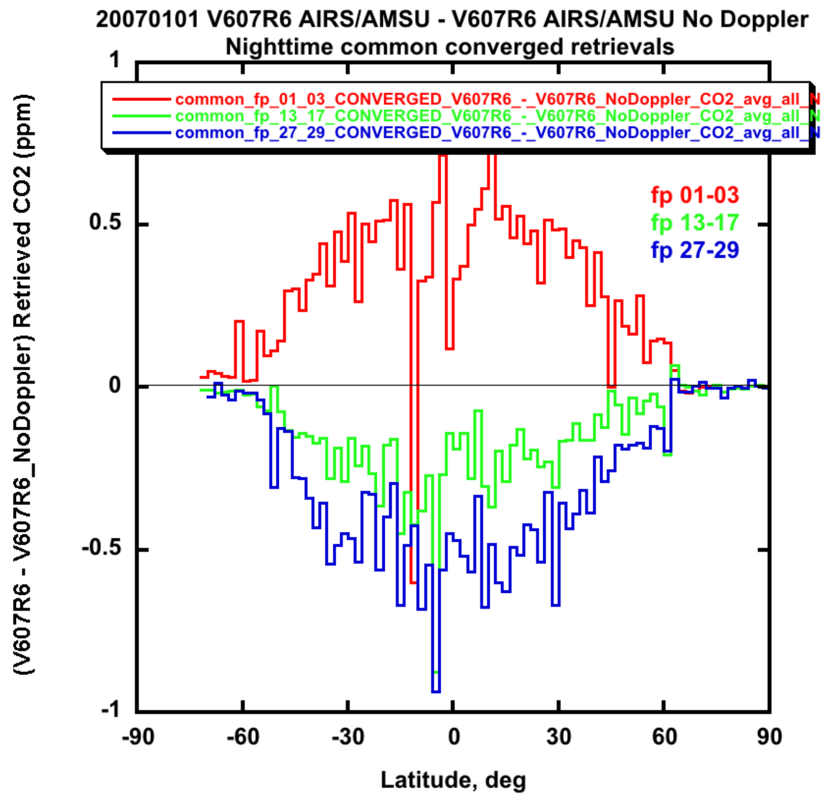
1 July 2007 Impact of SARTA V6 Doppler Correction on CO_2 Retrievals vs Latitude and Scan Angle



Doppler Correction in RTA V6 results in COS(lat) variation in retrieved CO2
Source is scene velocity along line of site
δCO2 ~ ±0.5 COS(lat) ppm at extreme scan angle





Ascending Orbit
Footprint 1 is Westward
(scene approaching due to Earth rotation)
Footprint 29 is Eastward
(scene receding due to Earth rotation)

Descending Orbit
Footprint 1 is Eastward
(scene receding due to Earth rotation)
Footprint 29 is Westward
(scene approaching due to Earth rotation)

1 July 2007 Zonal CO2 Lat/Scan Angle Variation
SARTA V6 (No Doppler) Compared to SARTA V108

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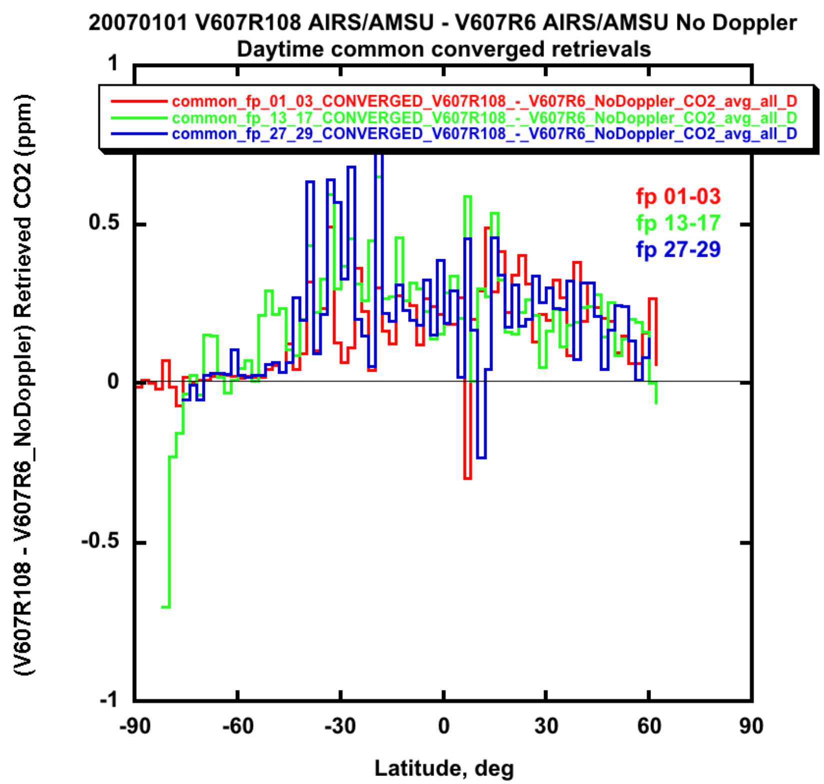
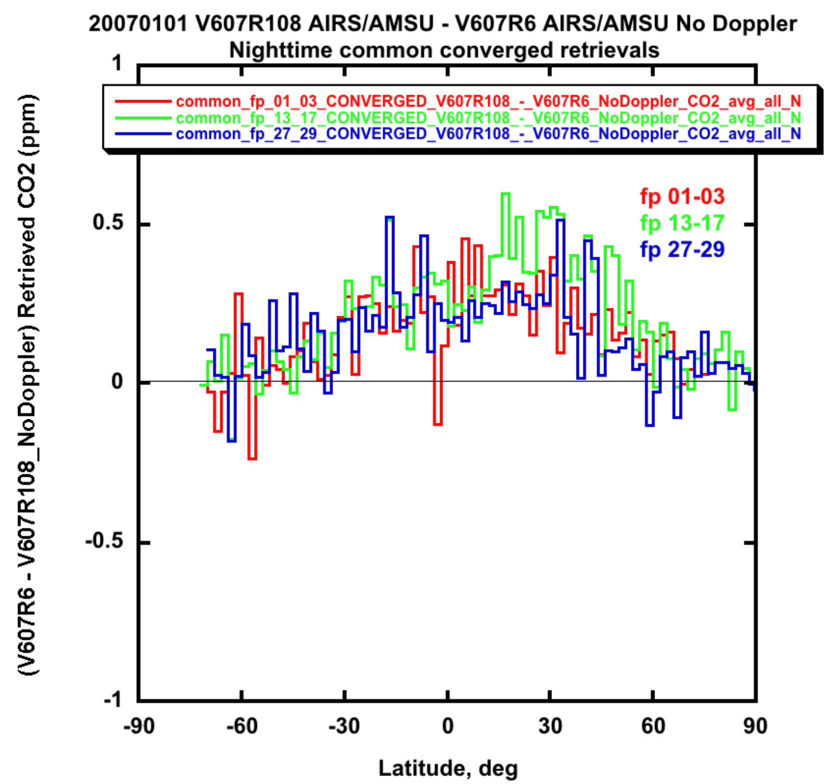
Residual Difference reflects difference in RTA coefficients excluding Doppler
V6 YOFFSET calculation includes derived knowledge of drift in focal plane and orbit-dependent shift of each channel wrt the center of its module in addition to Doppler
Result is δCO_2 ~ 0.25 ppm



Ascending Orbit
Footprint 1 is Westward
(scene approaching due to Earth rotation)
Footprint 29 is Eastward
(scene receding due to Earth rotation)



Descending Orbit
Footprint 1 is Eastward
(scene receding due to Earth rotation)
Footprint 29 is Westward
(scene approaching due to Earth rotation)

Transition to SARTA Version 6 – Initial Steps

- V6 Operational VPD CO2 retrieval must use SARTA Version 6
  - Initial implementation of V6 RTA in VPD PGE resulted in **2.5 hours/granule** execution time
    - Array setup required processing all 2378 channels, despite fact that VPD used far fewer
    - Initialization of 1350 AIRS footprints for 2378 channels required **15 minutes/granule**
    - Each call to SARTA (2378 channels) required **0.11 seconds (500 calls/cluster => 55 sec/cluster)**
  - Code optimization (still using full channel set) reduced execution time to **1.5 hours/granule**
    - Main driver code optimization reduced execution time approximately 0.5 hours/granule
    - Initialization execution time per granule reduced slightly
    - Each call to SARTA (2378 channels) required **0.09 seconds (=> 45 sec/cluster)**
      (this saves about 25 min/granule if ~150 clusters are being processed in a granule)
- Decision made to implement a hybrid, two-stage retrieval PGE
  (in case effort to fully modify code to support transition to subset of full channel set failed)
  - First stage configured to use fast SARTA V108 (or V107 If pre-Oct 2003)
    - Calculation done for subset of ~200 channels used by VPD
    - Assimilates V6 L2 products and performs CO2 retrievals
    - Identifies clusters whose retrievals failed and thus shall not be processed by the second stage
  - Second stage configured to use slower SARTA V6
    - Assimilates V6 L2 products and list of successful clusters from first stage
    - Performs CO2 retrievals to arrive at the final product
  - Execution time reduced at small cost in final yield (result: **1 hour/granule**)
    - Yield reduced by ~4% compared to single stage execution
      - i.e., stage 1 removes retrievals from consideration that would have been successful in stage 2
    - Execution time reduced by ~40% compared to single stage
      - Most retrievals removed by stage 1 would have failed in stage 2
      - Additional 4% of retrievals rejected in stage 1 that would not have been rejected in single stage V6 implementation are often outliers

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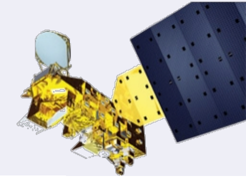
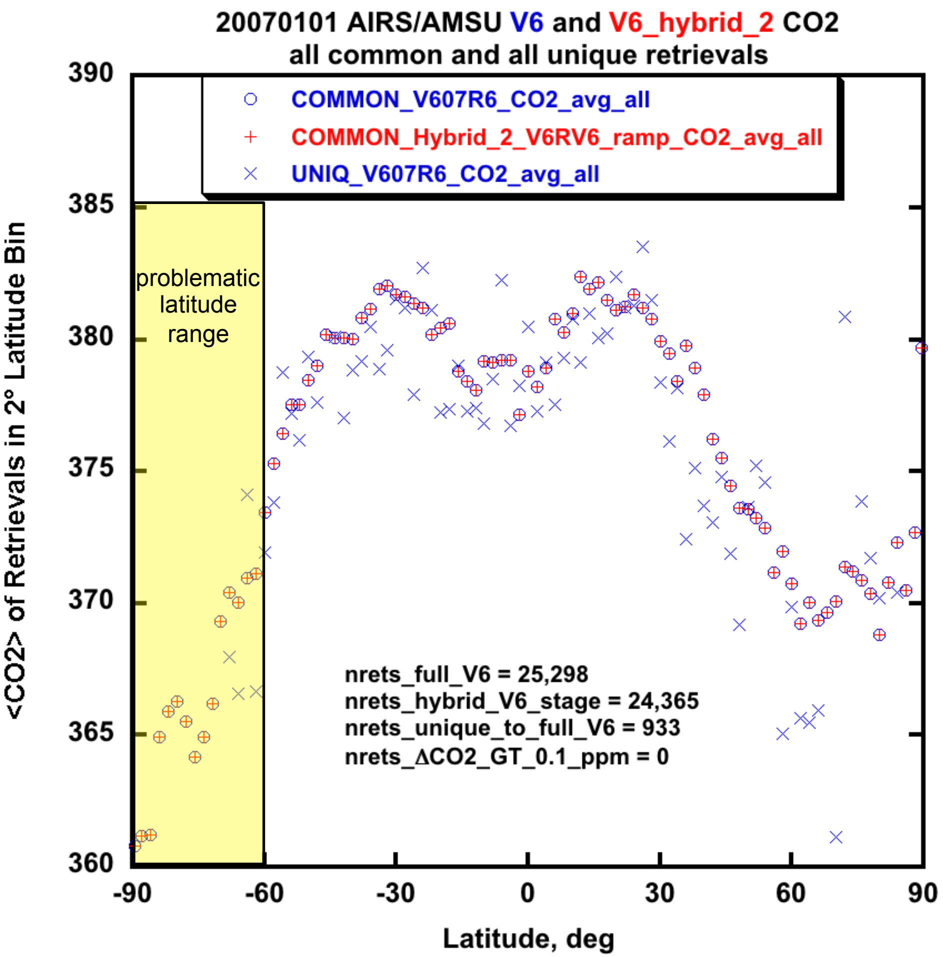
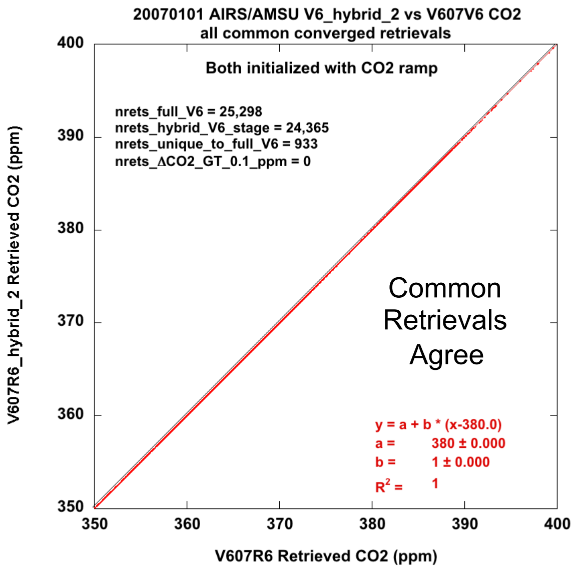
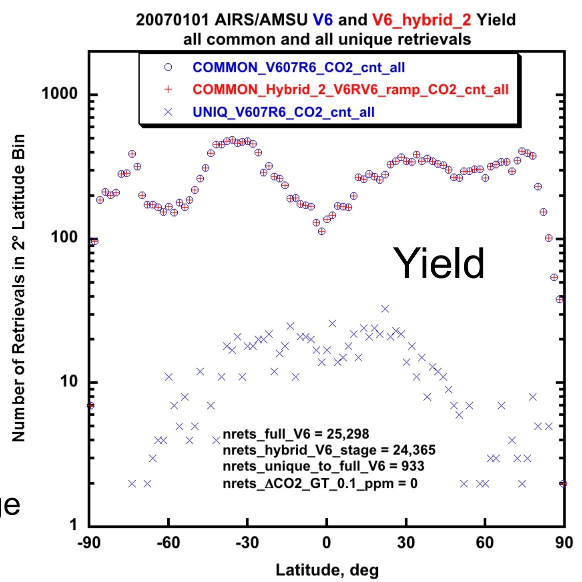
1 Jan 2007 Hybrid Stage 2 vs Single-Stage V6

(failed retrievals in Hybrid stage 1 are often outliers in single stage implementation)









Hybrid Stage 1 (fast RTA 108) used to pre-filter
Hybrid Stage 2 (slow RTA V6) operates on surviving clusters
Single-Stage (slow RTA V6) has no pre-filter

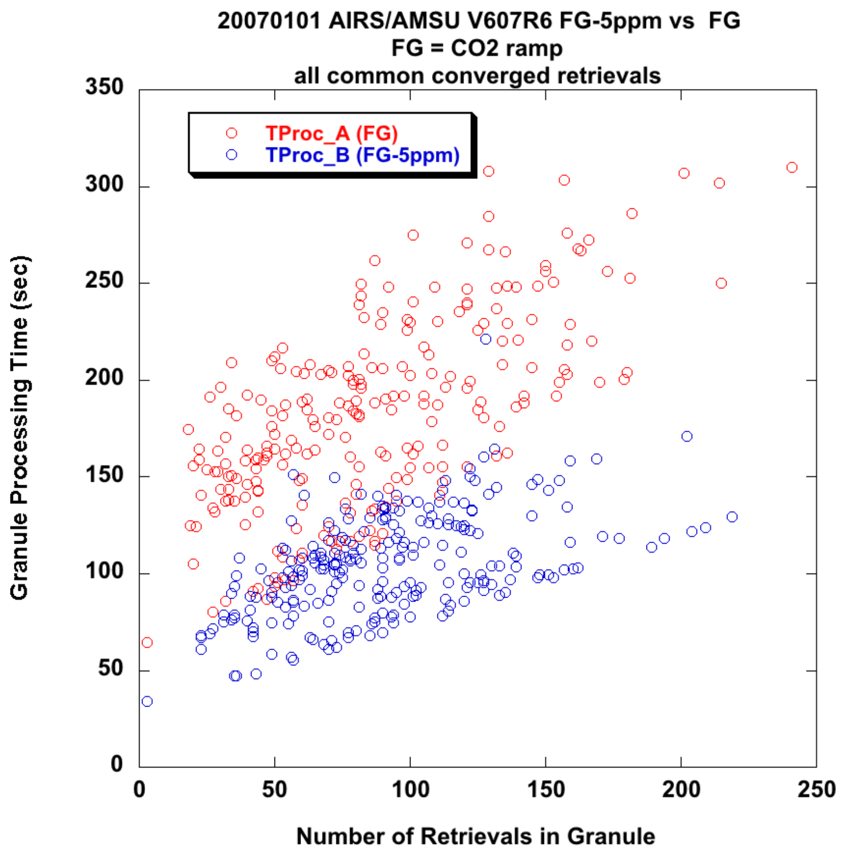
Additional 4% that fail Stage 1 pre-filter are outliers (runaways?) in Single-Stage
The 96% common to Hybrid and Single-Stage are digital match

Transition to SARTA Version 6 – Success at Last!

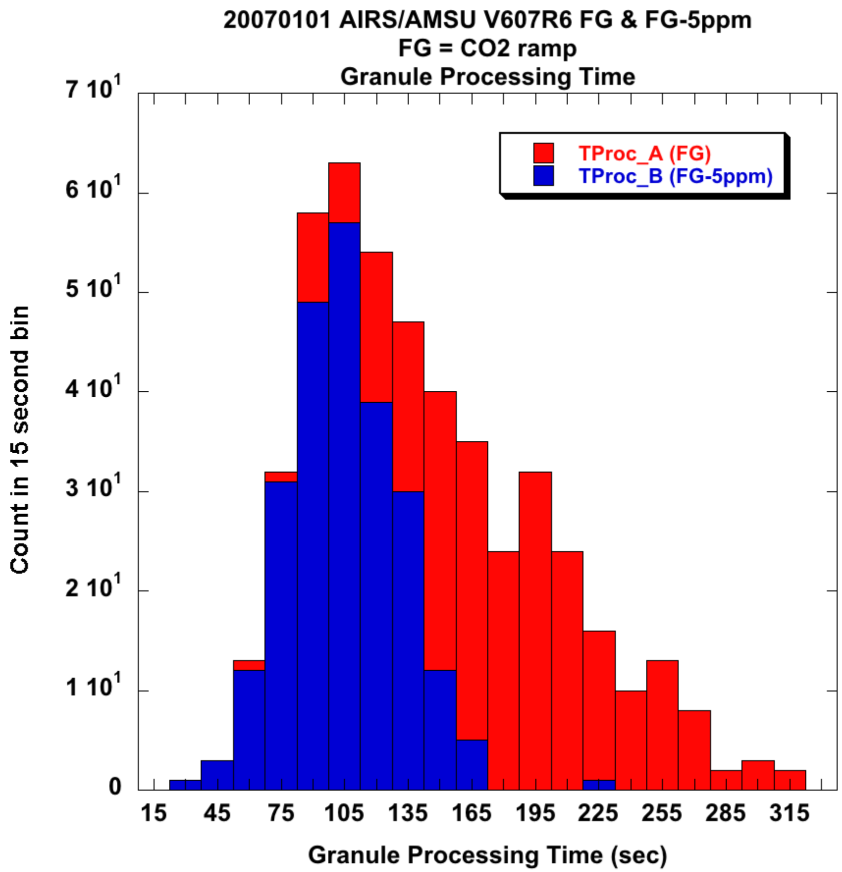
- Parallel software effort to modify code to permit execution of a subset of channels
  - Recap
    - Initial implementation of V6 RTA in VPD PGE resulted in **2.5 hours/granule** execution time
    - Code optimization (still using full channel set) reduced execution time to **1.5 hours/granule**
    - Two-stage retrieval hybrid reduces execution time to **1 hour/granule**
  - Extensive code modification of array handling and indexing permits execution for subset of channels
    - Main driver code and many FORTRAN modules modified
    - Initialization of 1350 AIRS footprints for 10 channels requires **10 seconds/granule**
    - Each call to SARTA (10 channels) requires **0.002 seconds (=> 1 sec/cluster)**
    - Execution time for single stage V6 is **2 minutes/granule**
    - The product from this fast implementation of V6 is a digital match to the product from the orginal slow implementation of V6
  - Fast V6 implementation allows expanded QC to detect and remove unstable, runaway solutions
    - A multi-stage implementation (330 possible 2x2 clusters within each granule)
      - First stage, operating on clusters made up of at least 3 AIRS L2 retrievals, perturbs the first guess by +δCO_2 and reports successful clusters and their retrieved CO_2 to second stage
      - Second stage, operating on successful clusters from first stage, perturbs the first guess by -δCO_2 and compares retrieved CO_2 to those reported by first stage. Clusters whose retrieved CO_2 agree within a pre-defined threshold are reported to the final stage
      - Final stage, operating on consistent-retrieval clusters reported out of second stage, assumes unperturbed first guess, applies final QC to successful retrievals and reports product
      - Product that results has been swept clean of runaway solutions and retrievals lacking sufficient sensitivity to the radiances
    - Initial tests underway, comparing results where FG is perturbed by ± 5 ppm

1 Jan 2007 Fast SARTA V6 Execution Time

Fast SARTA V6 Granule Execution Time
Offset between FG and FG-5ppm due to different loading on the processing units
(Tproc_B run on relatively "dry" CPU; Tproc_A run while others competed for resources)



Granule Processing Time
As a function of number of retrievals



Granule Processing Time
PDF

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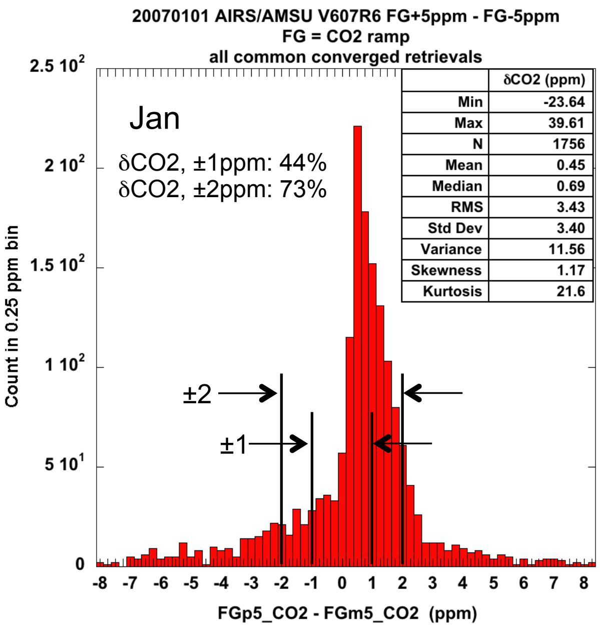
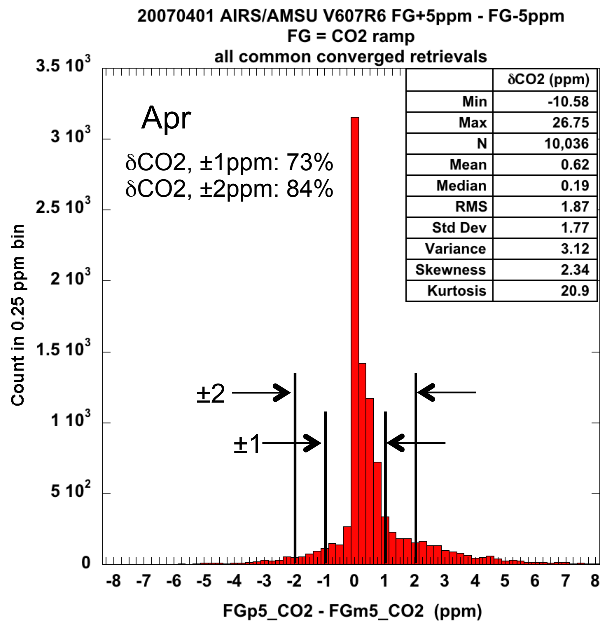
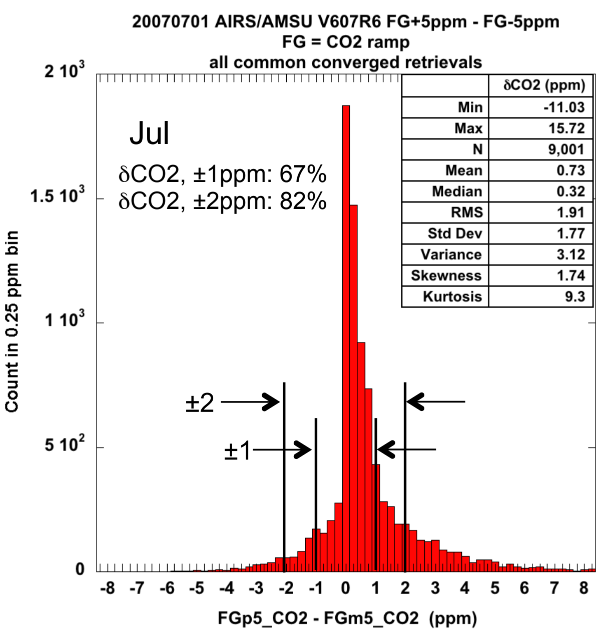
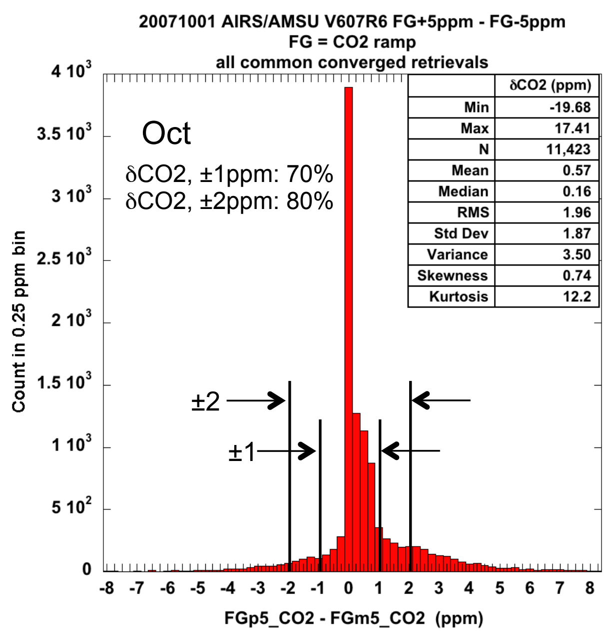
Robustness of CO2 Retrieval Against ± 5ppm Perturbation of FG
(1 Jan/Apr/Jul/Oct 2007)









Initial Test of Stability of VPD Solution Against Perturbation of FG by ±5 ppm

- Retrievals consistent within ±1 ppm for 10 ppm range of FG indicate their solutions are strongly constrained by radiances. Yield of retrievals satisfying this criterion is 44% to 70% of total yield.
- Retrievals consistent within ± 2ppm indicate their solutions are acceptably constrained by radiances but will be flagged. Yield of retrievals falling between ±1ppm and ±2ppm ranges between 10% to 29% of total yield.
- Solutions that move with FG by more than 20% of perturbation are not well constrained by radiances and are candidates for rejection. Yield of retrievals falling outside of ±2ppm ranges between 16% and 27% of total yield.
- Solutions disagreeing by more than perturbation of FG indicate runaways, i.e. solutions seeking adjacent local minima. These will be excised.

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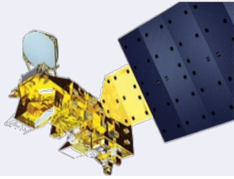
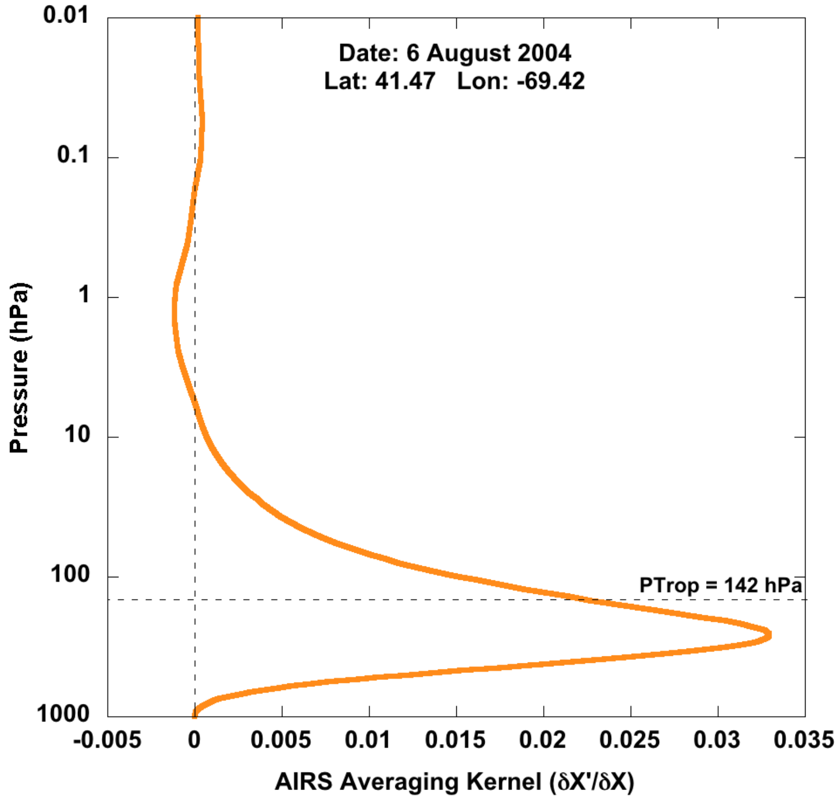


V6 QC Filtering by AK
Examples of Excellent and Pathological Calculated AKs

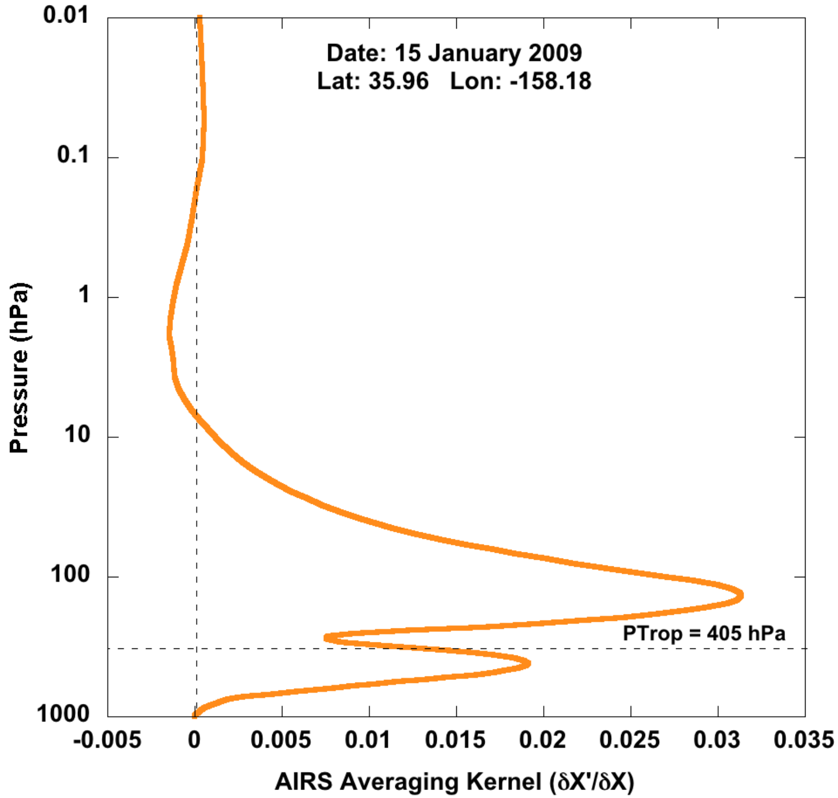
Additional QC to be applied at end of the final stage, when AK is calculated by perturbing each level individually and solving for CO2

Excellent AIRS CO2 AK



Calculated AK maximum sensitivity well below tropopause
Calculated AK tail nearly zero with tiny negative excursion

Pathological AIRS CO2 AK



Calculated AK exhibits double peak
with majority of sensitivity well above tropopause

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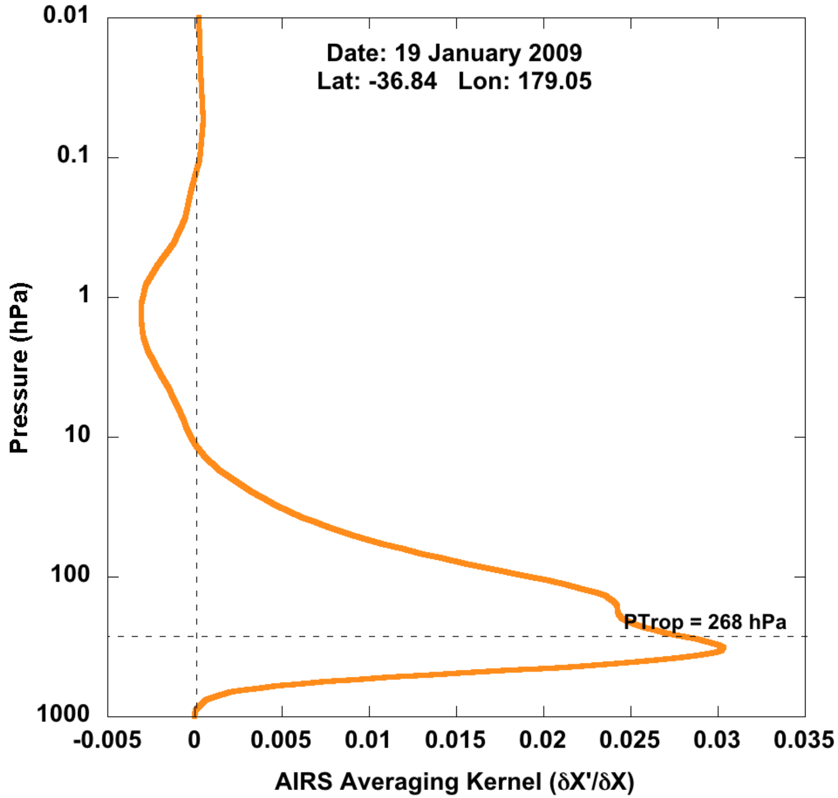
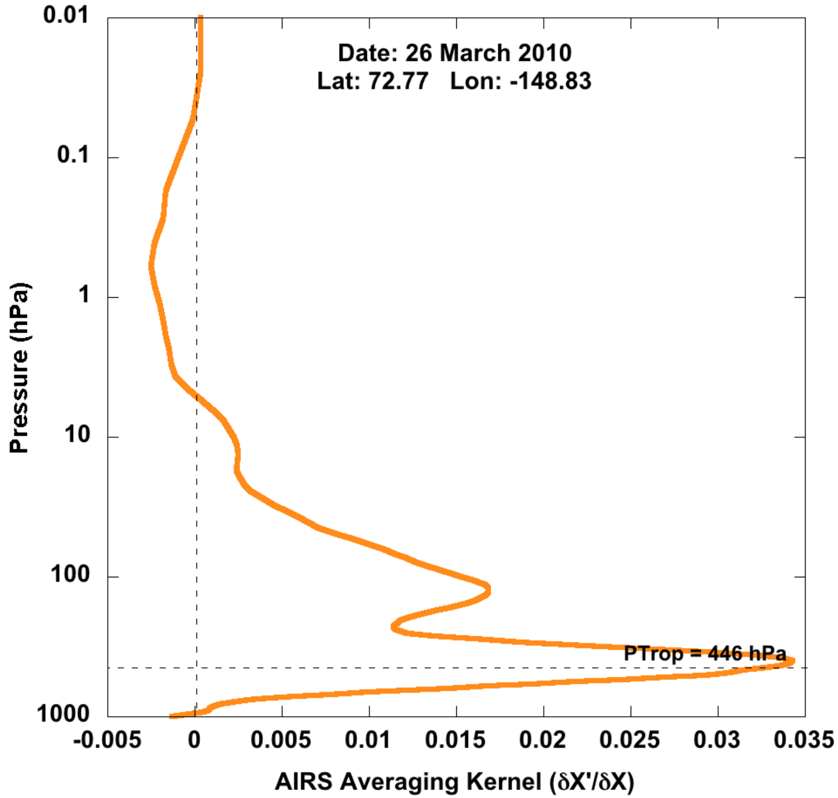
V6 QC Filtering by AK
Example of Questionable and High Latitude Calculated AKs

Two additional AK profiles that would fail CO2 AK QC
The profile to the right indicates a common problem for high latitude retrievals



Calculated AK maximum sensitivity straddles tropopause
Calculated AK tail exhibits negative excursion



Calculated AK maximum sensitivity above tropopause
Calculated AK exhibits double peak
with majority of sensitivity well above tropopause
Calculated AK trail exhibits negative excusion

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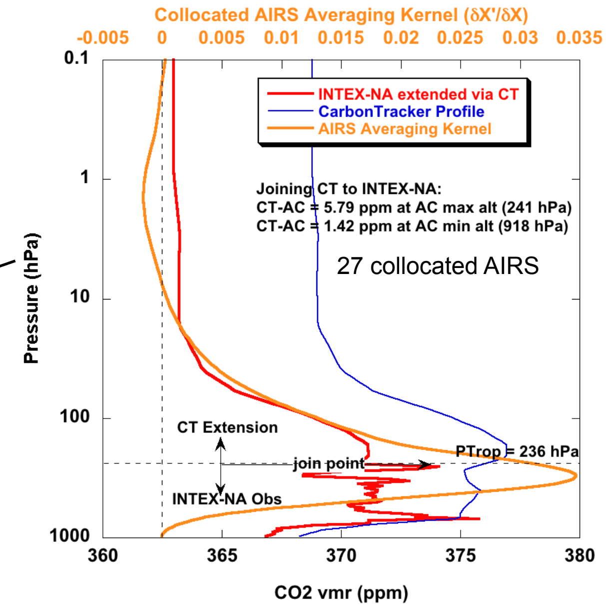
Interim Validation – INTEX-NA

INTEX-NA profiles extended using CT2013B model profiles

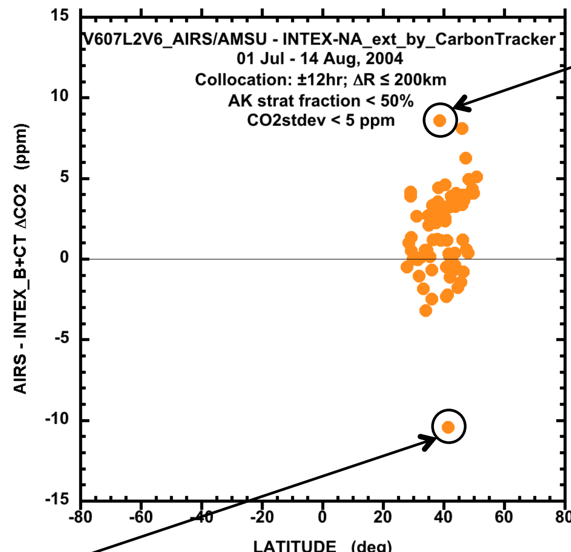
- At highest aircraft altitude, CT profile joined to aircraft profile
- Result convolved with AIRS AK to arrive at value to compare to the average of AIRS collocated retrievals within ±12 hr and ΔR ≤ 200 km

Note: At times CarbonTracker appears to have some difficulty getting the tropopause pressure correct at high latitudes. This will result in error when calculating the transport of the trace gases into the stratosphere.
(see interesting paper in ACPD by F. Deng et al, www.atmos-chem-phys-discuss.net/15/10813/2015/ doi:10.5194/acpd-15-10813-2015)

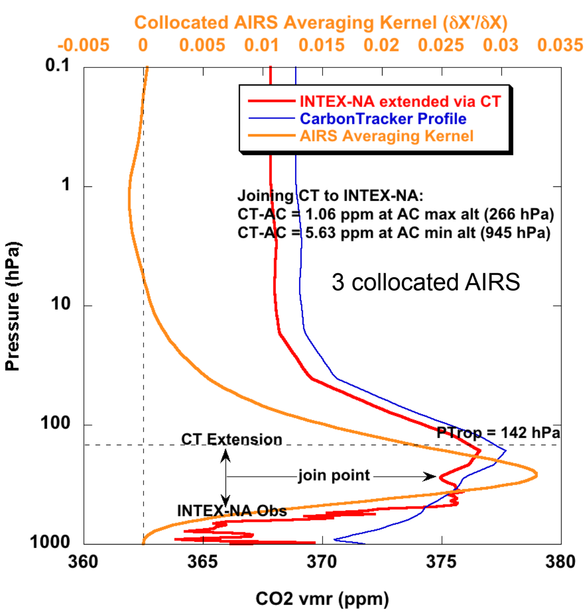
INTEX-NA Profile: 20040715_prof03
Lat: 46.02 Lon: -85.42
AIRS_CO2 - INTEX-NA_ext_CT_CO2 = 8.10 ± 3.1 ppm



In this case, the roll-off of CT CO2 vmr appears to begin approximately 100 hPa higher in atmosphere than the location of the tropopause determined by temperature profile lapse rate



INTEX-NA Profile: 20040806_prof01
Lat: 41.47 Lon: -69.49
AIRS_CO2 - INTEX-NA_ext_CT_CO2 = -10.41 ± 4.2 ppm



A discrepancy of ~4 ppm between CT and in situ measurements throughout the troposphere is rare. The dynamical origin of the air parcels sampled of CO2 should be taken into account in the matchup criteria through a constraint on the free tropospheric temperature at 700 hPa in the manner of Wunch et al (2011) or potential temperature allowing relaxation of spatial constraint and increasing number of collocated AIRS retrievals.

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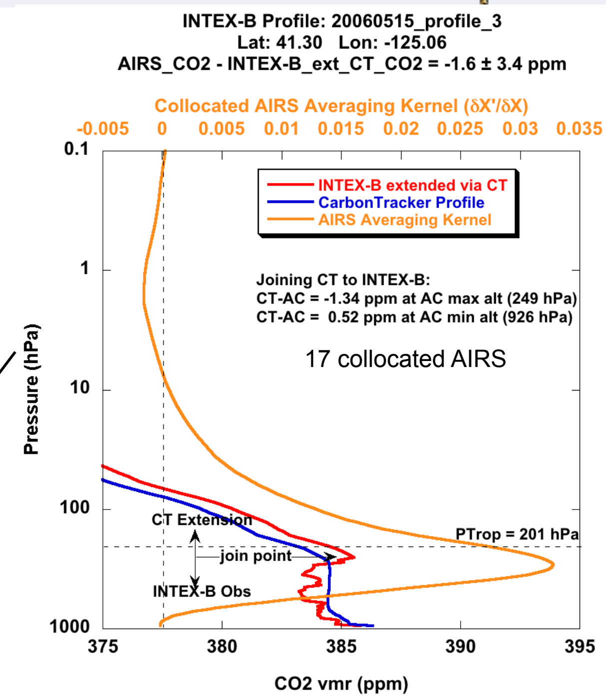
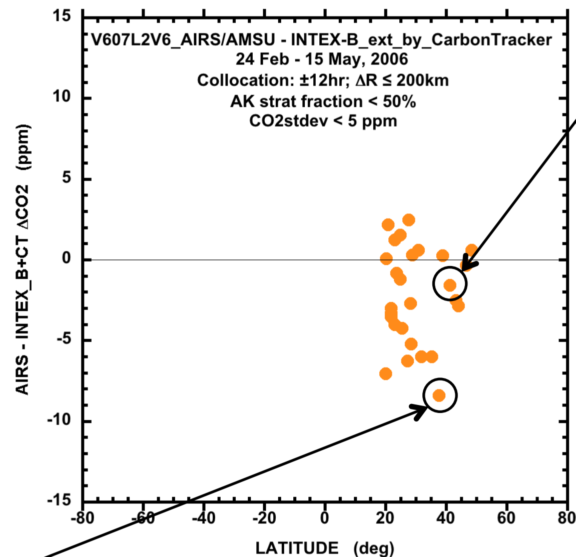
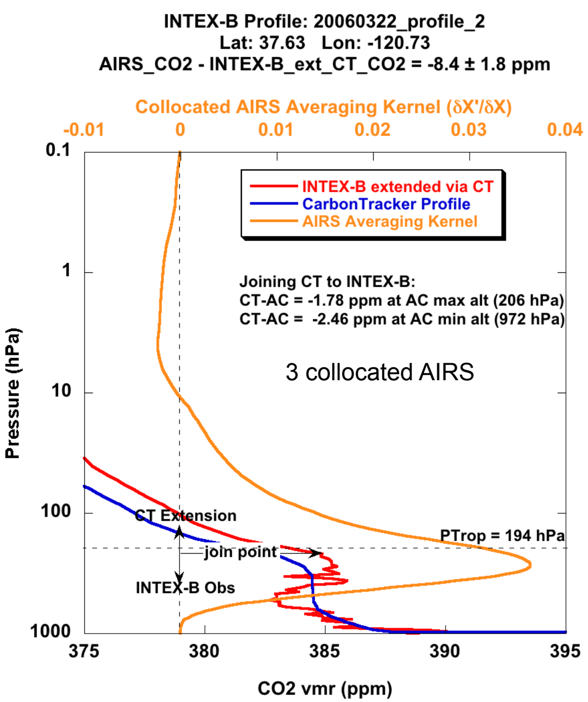
Interim Validation – INTEX-B

INTEX-B profiles extended using CT2013B model profiles

- At highest aircraft altitude, CT profile joined to aircraft profile
- Result convolved with AIRS AK to arrive at value to compare to the average of AIRS collocated retrievals within ±12 hr and ΔR ≤ 200 km







In both cases, the roll-off of CT CO2 vmr begins at the location of the tropopause determined by the temperature profile lapse rate, and the match between the in situ measurements and CT2013B in the troposphere is very close. The AIRS Aks also appear to be well-behaved and separated equally from the tropopause.
The dynamical origin of the air parcels sampled of CO2 should be taken into account in the matchup criteria through a constraint on the free tropospheric temperature at 700 hPa in the manner of Wunch et al (2011).

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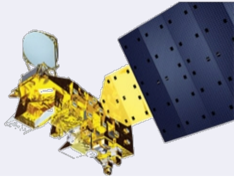
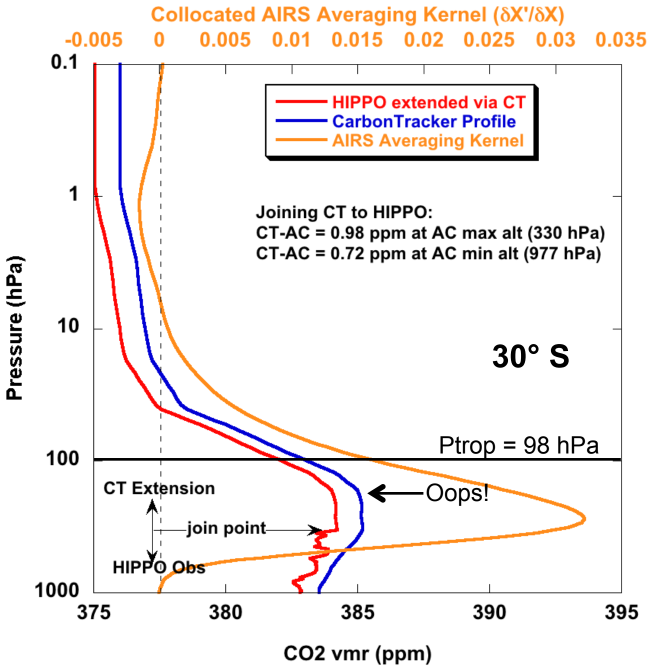
HIPPO Profile Extension via CarbonTracker for Validation of Collocated AIRS CO_2 Retrievals

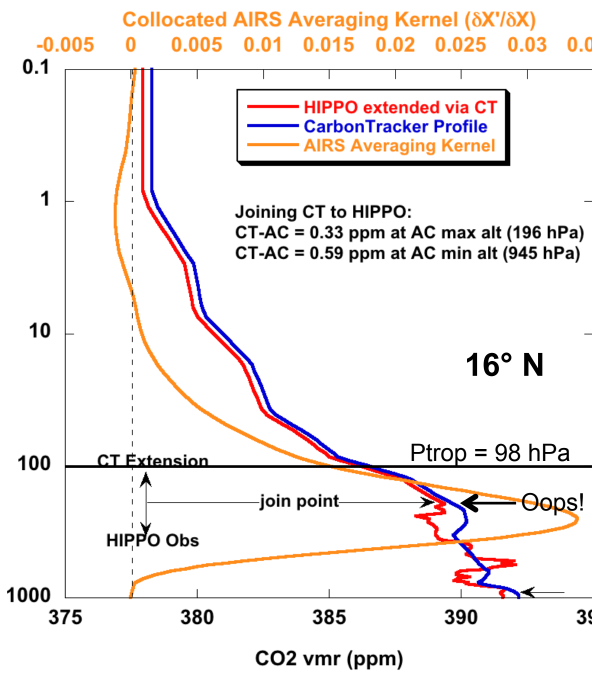


Extend the *in situ* measurements to higher altitude via the CarbonTracker vertical transport model that assimilates low altitude and surface measurements allows the validation effort to include all HIPPO profiles in the analysis rather than only Deep Dip Profiles

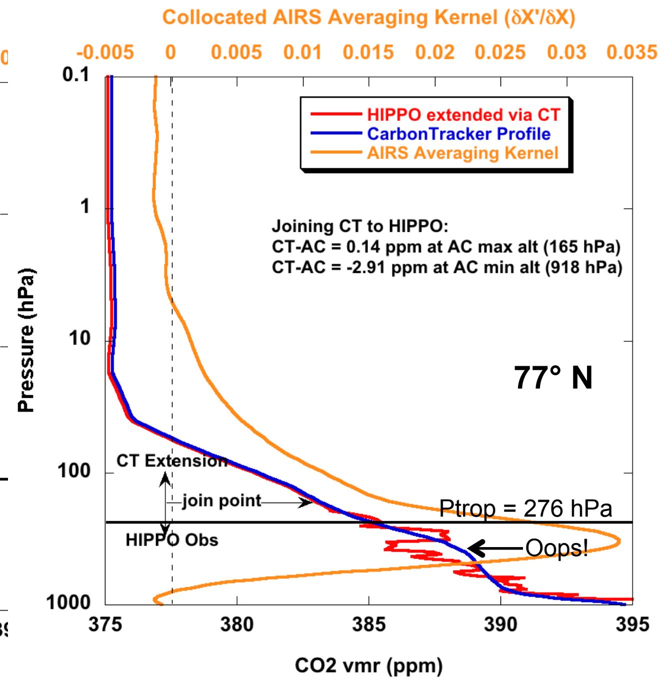
HIPPO-1 Profile: 2009_019_1_06_068
Lat: -31.75 Lon: -178.21
AIRS_CO2 - HIPPO_ext_CT_CO2 = +5.2 ± 4.9 ppm



HIPPO-3 Profile: 2010_090_3_04_044
Lat: 15.71 Lon: -158.69
AIRS_CO2 - HIPPO_ext_CT_CO2 = -7.6 ± 7.1 ppm



HIPPO-1 Profile: 2009_012_1_03_025
Lat: 77.17 Lon: -156.51
AIRS_CO2 - HIPPO_ext_CT_CO2 = -7.0 ± 10.0 ppm



Validating collocated AIRS retrieved CO2 with HIPPO measured CO2 profiles is complicated because:

- Tropopause shifts closer to pressure of AK maximum at higher latitudes
  - More so in the SH winter time at the mid-latitudes
- Tropopause pressure is very close to that of AK peak for |lat| > 45°

CT2013B data sets are available at
ftp://aftp.cmdl.noaa.gov/products/carbontracker/co2/CT2013B

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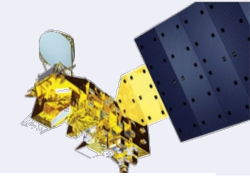
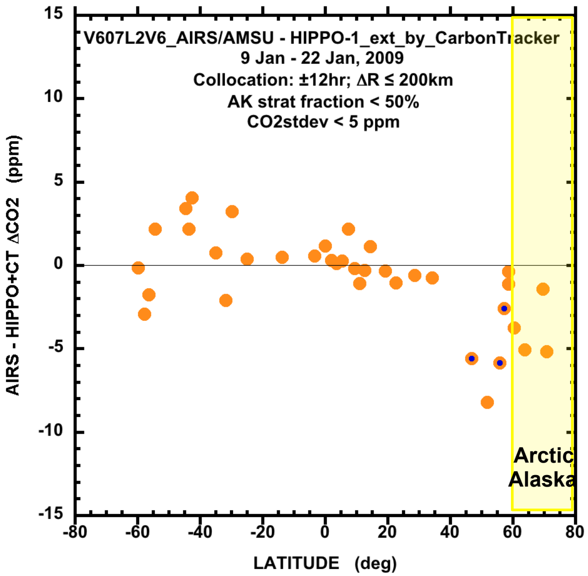
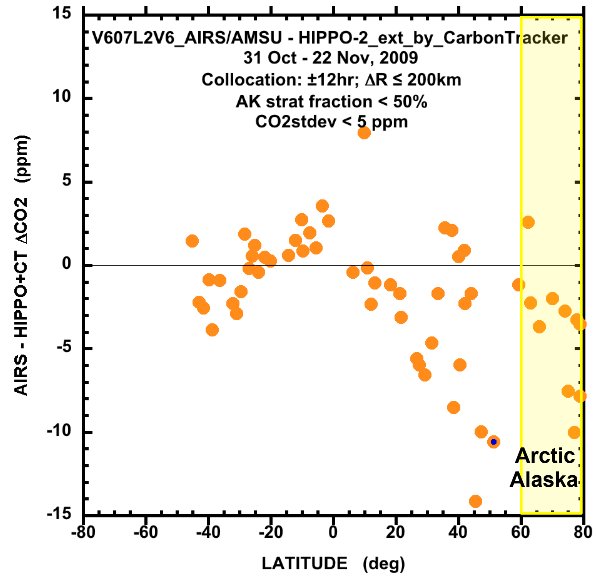
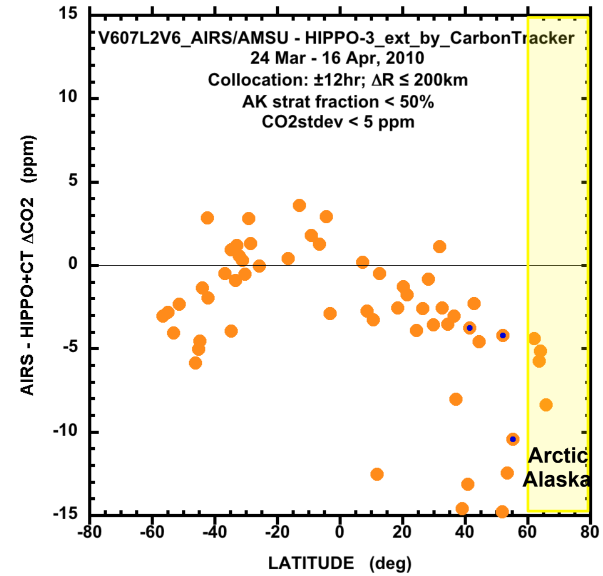
Interim Validation – HIPPO

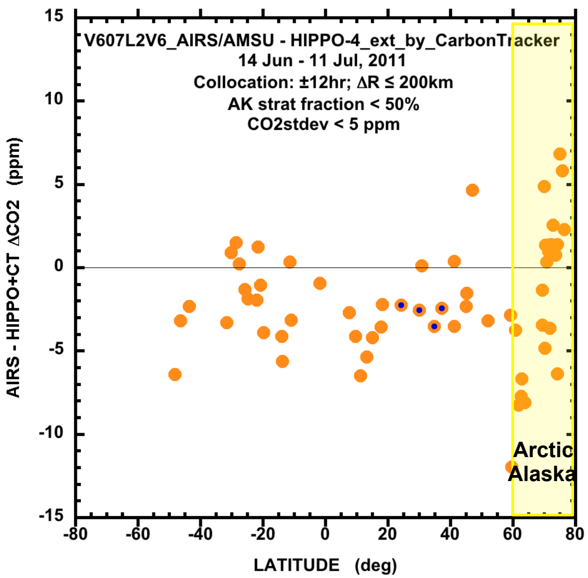


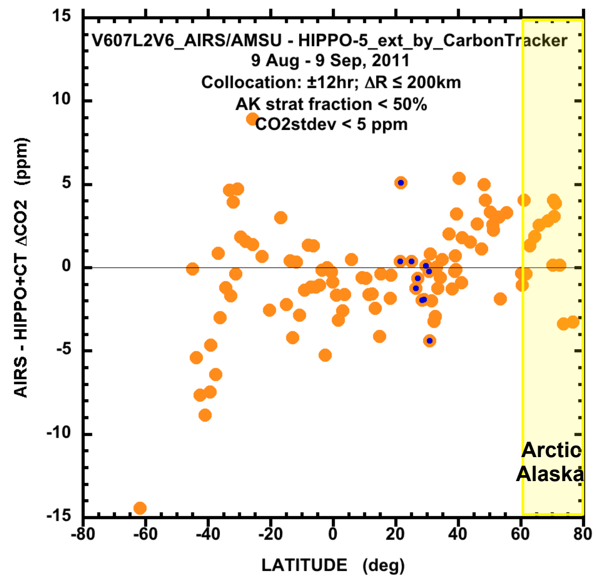


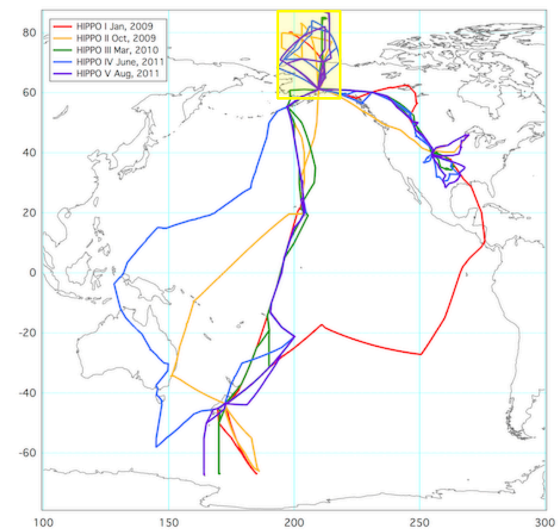




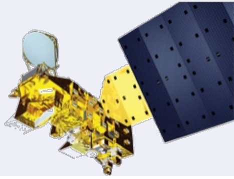
Collocations with blue centers are over NA land mass south of 60N



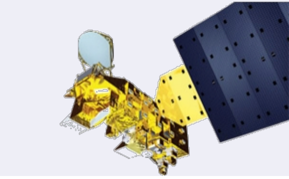




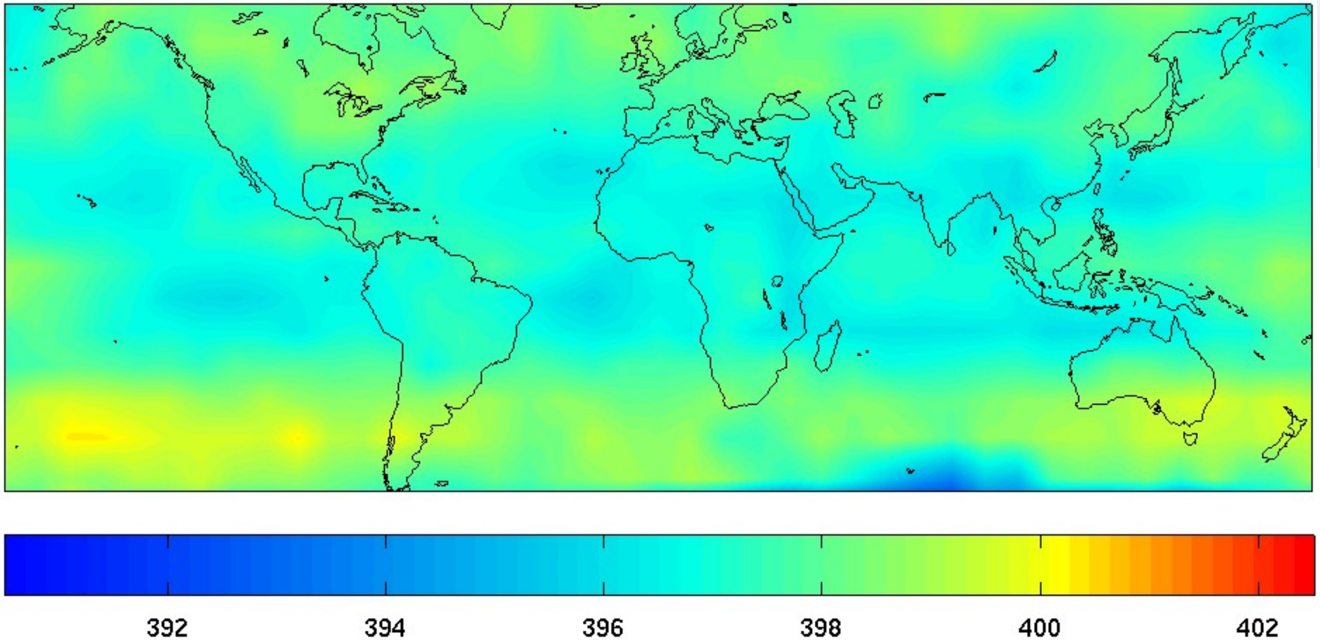
Next Steps

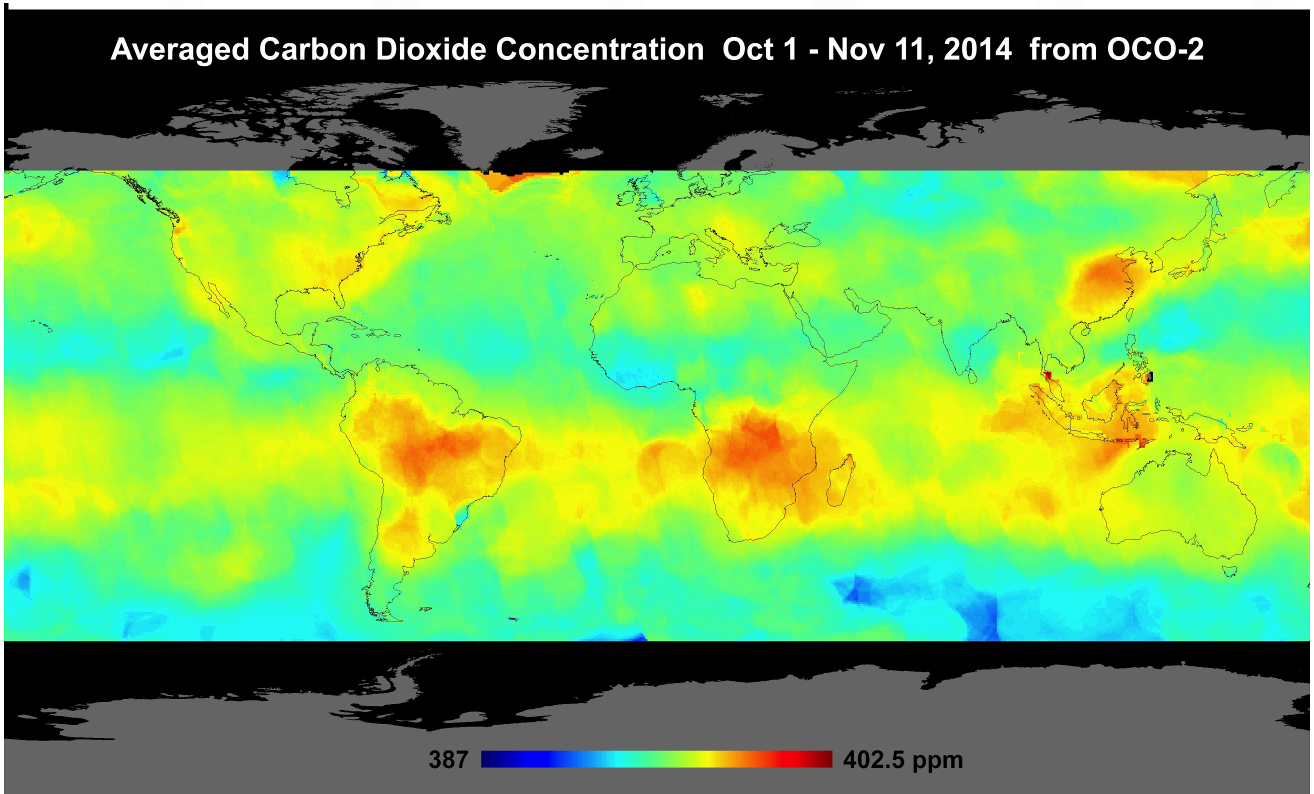


- Next Steps
  - Stability of CO2 retrieval with respect to fine structure in temperature profile and bias in stratosphere temperature
    - Quantify impact, if any, of smoothing temperature profile with moving boxcar
    - Quantify impact of bias by perturbing the stratospheric temperature
  - Validation via *in situ* airborne campaigns
    - Test T@700 hPa and potential temperature constraints for added collocation criterion to refine selection of coincident retrievals (may allow relaxation of spatial constraints)
    - Reanalyze INTEX-NA, INTEX-B and HIPPO
    - Add START08, ARCTAS, ICEBRIDGE
  - Direct comparison to CarbonTracker
    - All AIRS CO2 retrievals Jan/Apr/Jul/Oct for seasonal variation over globe
  - QC optimization
    - Emphasis on removing bias at high northern latitudes
    - Eliminate
      - Runaway solutions
      - Solutions with unacceptably low sensitivity to radiances
      - Solutions with unrealistic AKs
  - Operationalize code and Document (ATBD and User Doc)
    - Deliver to Operations Team for creation of V6 CO2 tropospheric product
    - Create ATBD and User Documentation
  - Probe deeper in troposphere



AIRS CO_2
1-31 Oct 2014
~400 hPa
(no sensitivity to variations beneath 700 hPa)





OCO-2 CO_2
Total
Column